Optical attenuator based on phase modulation
of a spatial light modulator

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In this Letter, we propose an optical attenuator based on the phase modulation of a spatial light modulator (SLM). In this system, we use two polarized beam splitters (PBSs) to control the polarized light and one SLM to modulate the phase of the polarized light. In the initial state, the light beam is divided into p-light and s-light when it passes through the first PBS. When the light passes through the second PBS, s-light is reflected and p-light is detected by the CCD camera. By loading different grayscales on the SLM, p-light changes its polarized state to s-light. The light power can be attenuated during the loading process. Our experiment shows that the system can obtain a wide optical attenuation from 1–27.2 dB. When loading two grayscales, the SLM has a fast switching time of 25 ms under a low actuated voltage of 5.5 V. The response time of the optical attenuator depends on the switching time of the SLM. Therefore, the system can also have a fast response time. By using the method of spatial multiplexing and adding two mirrors in the system, it can also be extended into a 1×2 optical switch. The results verify its feasibility. The optical attenuator has wide applications in photonic signal processing and fiber-optic communication.

OCIS codes: 230.6120, 220.4830, 110.1220.
doi: 10.3788/COL201513.082301.

Variable optical attenuators (VOAs) have been intensively studied in recent years because they are essential to applications such as wavelength division multiplexing systems, photonic signal processing, and fiber-optic communication. Various VOAs have been proposed based on technologies such as micro-electromechanical systems (MEMS)[1–8], thermo-optics[9–11], micro-fluidic[12–20], and liquid-crystals (LCs)[21–24]. MEMS-based attenuators usually use micro-fabrication processes to create moving mirrors to achieve attenuation by changing the mirror reflection angles and directions[3–5]. Although these devices have a fast response time and can achieve relative high optical attenuation, the microshutters or micromirrors indicate a reliability issue. Some researchers have proposed a thermo-optics-based optical attenuator. A heating electrode is used to tune the refractive index of the waveguide material. It can attain a low operating power of 30 mW and less than 0.1 dB of the insertion loss. However, the large thermo-optic effect of polymer materials renders it difficult to avoid a temperature dependence[10]. Microfluidic-based optical attenuators mainly employ a dyed liquid to absorb the light or alter the refractive index of the liquids within the microchannels to control the beam. They are easy for in-plane integration but the fabrication procedures, such as multistep photolithography and soft lithography, are complicated[14–16]. LCs have been considered an excellent alternative material for making optical components because of their low loss, low power consumption, and no moving parts. Several types of LC-based VOAs have been proposed such as nematic LC VOAs, polymer-network LC-based VOAs, and LC grating-based VOAs.

Recently, the spatial light modulator (SLM) has attracted researchers' attention due to its unique advantages of programmability, high resolution, and light weight. In this Letter, we propose an optical attenuator based on the phase modulation of an SLM. By changing the grayscale encoded on the SLM, we can gradually change the polarized state of the polarized light. Our work shows that the system can obtain a wide optical attenuation from 1 to 27.2 dB. The response time of the optical attenuator depends on the switching time of the SLM, and the measured response time is 25 ms under a low actuated voltage of 5.5 V. By using the method of spatial multiplexing and two mirrors, it can also be extended into a 1×2 optical switch.

The operating mechanism of the proposed optical attenuator system is depicted in Fig. 1. It consists of
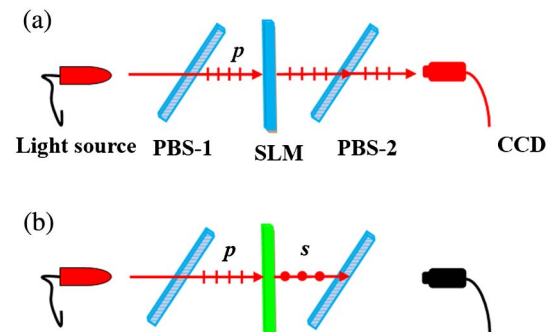

Fig. 1. Principle of the optical attenuator: (a) initial state; (b) loading a grayscale with phase π on the SLM.

two polarized beam splitters (PBSs) and a SLM. In the initial state, no grayscale is loaded on the SLM. When the light illuminates PBS-1, s-light is reflected by PBS-1 and p-light can pass through the SLM and PBS-2. Consequently, the CCD camera can detect p-light, as shown in Fig. 1(a). The polarization state of the incident light is changed by retardation control by the SLM. When the SLM is loaded with different grayscales gradually, phase retardation results, and consequently p-light changes its polarized state. It will be partially reflected by PBS-2 during the modulation process. Consequently, the light power captured by the CCD camera decreases. If we load a grayscale with phase π by the modulation of the SLM, p-light changes its polarized state to s-light. In this state, the light is reflected by PBS-2. The CCD camera cannot detect any light, as shown in Fig. 1(b). In this way, the system can achieve the function of an optical attenuator. In theory, the system can realize 100% light attenuation.

The parameters of the laser are listed: polarization state (linear vertical), extinction ratio ($>100{:}1$), output power (2 mW), and beam divergence full angle (1.5 mrad). In our work, the SLM is developed by the Xi'an Institute of Optics and Precision Mechanics, China. The model of our SLM is FSLM-VIS. The SLM is the reflection type with a pixel number of 8 μm and the reflectivity of 60%. Three main contributions of the reflectivity are listed: reflection of the glass window, the absorption of the LC layer, and the reflection of the internal reflection film. The aperture ratio of each pixel is 87%, and consequently the pixel gap is ~1.08 μm. The insertion loss and extinction ratio of the PBS are ~0.2 dB and $>500{:}1$, respectively. First, we used an interferometer and a red laser with $\lambda = 633$ nm to measure the phase modulation of the SLM when loading different gray values of the grayscales. The measured results are shown in Fig. 2. As we can see from Fig. 2, when the SLM was loaded on the grayscale with a value of 75, the phase modulation can reach π.

The system was set up as depicted in Fig. 1. We used a red light as the light source and continually loaded the grayscales with values from 0–75. Figures 3(a)–3(f) show the results with gray values 0, 15, 30, 45, 60, and 75,
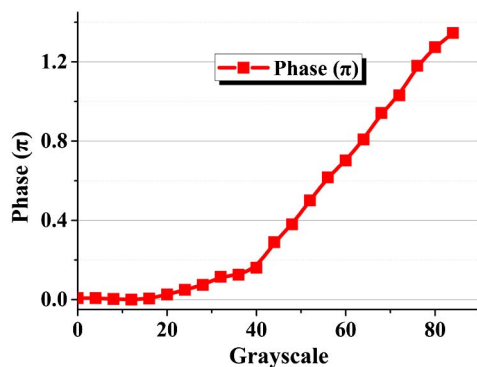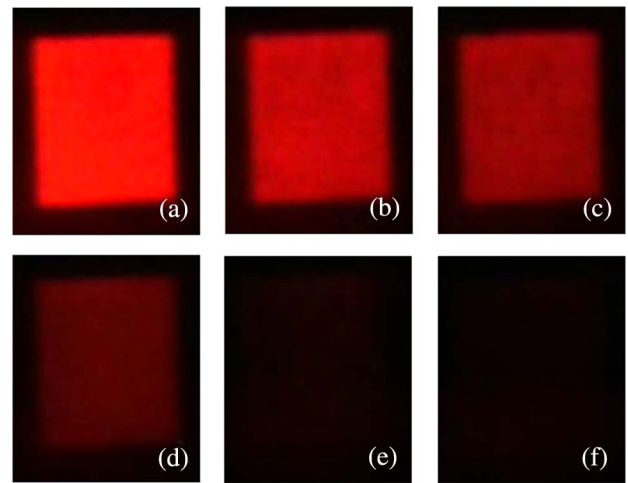

Fig. 3. Results of loading different grayscales on the SLM: (a) value = 0; (b) value = 15; (c) value = 30; (d) value = 45; (e) value = 60; (f) value = 75 (Media 1).

respectively. The results were also recorded (Media 1). In the initial state, when the SLM loaded on the grayscale with a value of 0, there was nearly no phase modulation. The optical attenuation was ~1 dB, as shown in Fig. 3(a). When the SLM loaded on the grayscale with the value of 75, the phase modulation can reach π. In this state, p-light change its polarized state into s-light. Consequently, in theory, the CCD camera cannot detect any light, as shown in Fig. 3(f). We also measured the attenuation when loading different grayscales on the SLM, as shown in Fig. 4. In the initial state, the light power was measured to be ~52 μW. When loading the grayscale with a value of 75 on the SLM, the measured light power was 0.1 μW. Consequently, the maximum light attenuation is ~27.2 dB. We use the SLM to modulate the phase of the polarized light. The response time of the system depends on the switching time of the SLM, and consequently the measured response time was 25 ms under a low actuated voltage of 5.5 V.

The system can also be expanded into a 1×2 optical switch when adding two more mirrors in the system. The extended system is shown in Fig. 5. It consists of two
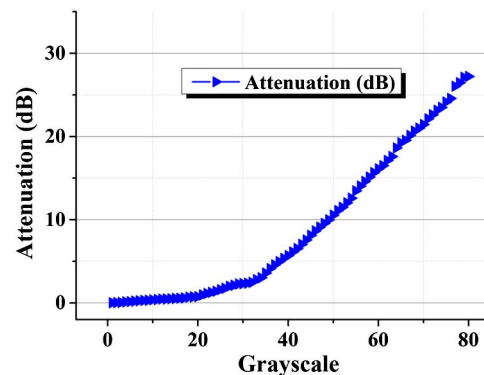

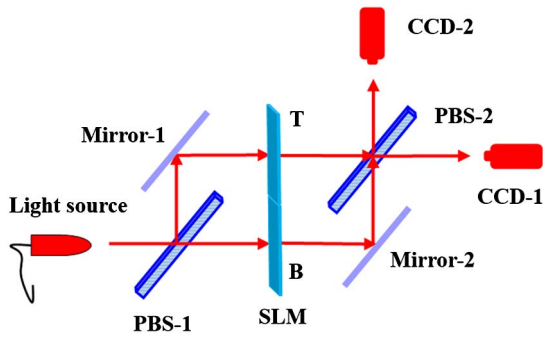Fig. 2. Phase modulation of the SLM when loading different grayscales.

Fig. 4. Attenuation when loading different grayscales on the SLM.

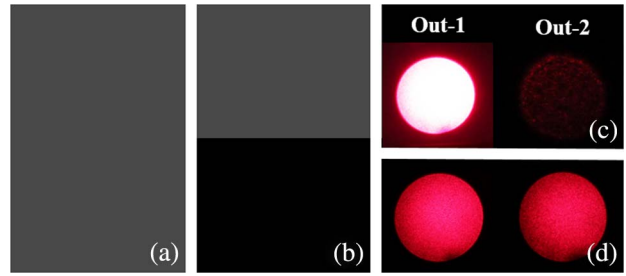Fig. 5. Structure of the extended 1×2 optical switch.

Fig. 6. Grayscales loaded on the SLM and the results of light-on and light-off: (a) grayscale in $(1, 1)$ state; (b) grayscale in $(1, 0)$ state; (c) result of $(1, 1)$ state; (d) result of $(1, 0)$ state.

PBSs, a SLM, and two mirrors. We used the spatial-multiplexing method to divide the SLM into two parts, named T and B. Two different grayscales were generated and loaded on half the area of the SLM. In the initial state, no grayscales were loaded on the T-part and B-part, and we defined this state to be $(0, 0)$. When the light illuminated PBS-1, p-light passed through the B-part and PBS-2. Meanwhile, s-light was reflected by PBS-1 and PBS-2. In this state, CCD-2 can detect non-polarized light and CCD-1 cannot detect any light. When we loaded a grayscale with the value of 75 on the T-part, we defined this state to be $(1, 0)$. In this state, p-light passed through the B-part and PBS-2. We can obtain p-light from CCD-2. The s-light changed its polarized state into p-light. We can also receive p-light on CCD-1. Consequently, CCD-1 and CCD-2 can both detect the polarized p-light. The mechanism of other states such as $(0, 1)$ and $(1, 1)$ are the same with the aforementioned discussions. Table 1 shows all the states of the 1×2 optical switch after the modulation of the SLM.

The grayscales loaded on the SLM and the results are shown in Fig. 6. In the state of $(1, 1)$, the gray values of the grayscales loaded on the T-part and B-part are both 75, as shown in Fig. 6(a). The result of state $(1, 1)$ is shown in Fig. 6(c). In the state of $(1, 0)$, the gray values of the grayscales loaded on the T-part and B-part were 75 and 0, respectively, as shown in Fig. 6(b). The result of state $(1, 0)$ is shown in Fig. 6(d). Other states are similar with the previous ones. From the results, we can see that the system can be extended to a 1×2 optical switch when the SLM loaded certain grayscales. In our work, the laser beam is indeed 2 mW. However, the light spot is very narrow. To make the beam illuminate the SLM, the beam is expanded. We measured the incident light before illuminating the system. The intensity is ~ 0.4 mW. In the state $(1, 1)$, the intensity of Out-1 and Out-2 are ~ 110 and 0.01 μW, respectively. In the state of $(1, 0)$, the intensity of Out-1 and Out-2 are ~ 54 and 50 μW, respectively. In the system, the measured insertion loss of the system is ~ 5.6 dB, and the crosstalk of the system is mainly due to using the spatial-multiplexing method in the SLM. The measured insertion loss of the system is ~ 0.5 dB. In the first experiment, the light attenuation can just reach ~ 27.2 dB. In theory, the light attenuation can reach 100%. The main reason of this range may be due to the incompleteness of polarization optics such as the laser, PBS, and SLM. The quadrature leakage component would degrade attenuator performance. Similarly, as shown in Fig. 6(c), in the state $(1, 1)$, CCD-2 can still detect the light although it is very week. The reason may be that the change of the phase cannot just reach π when we load the grayscale with the gray value of 75. There is still some s-light reflected by PBS-2. Consequently, a very weak light is detected by CCD-2. We can solve this issue by measuring the grayscale modulation of the SLM accurately and loading a suitable grayscale on the SLM. How to improve the property of the optical attenuation system is also an aspect of our future work.

In conclusion, we demonstrate an optical attenuator based on the phase modulation of a SLM. By using two PBSs and changing the grayscales loading on an SLM, we can change the polarized states of the polarized lights to achieve the function of optical attenuation. Our work shows that the optical attenuation can be varied from 1–27.2 dB. The system also has a fast response time of 25 ms and a low voltage of 5.5 V. The system has the features of efficient performance and insensibility to polarization of the signal light. The optical attenuator has wide applications in photonic signal processing and fiber-optic communication.

Table 1. State of the 1×2 Optical Switch after Modulation of the SLM

Input	T	B	Polarization	Output	
Light source	1	1		1	
	0	0		2	
	1	0	p	1	2
	0	1	s	1	2

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